

# Segmented thermoelectric generators: Impact of junction temperature variation on the series circuit's properties

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(Dated: March 8, 2013)

We present and analyze a model of a system constituted of two thermoelectric generators (TEGs) thermally and electrically connected in series. For simplicity the parameters of both TEGs are assumed to be temperature-independent. The derivation of the equivalent electrical series resistance yields an unexpected term whose meaning and impact are discussed. We demonstrate that this term must exist as a consequence of thermal continuity at the interface, since it is related to the variation of the junction temperature between the two TEGs as the electrical current varies. We then derive an expression for the equivalent series figure of merit and use it to discuss the approach of thermoelectric compatibility. Finally we highlight the strong thermal/electrical symmetry between the parallel and series configurations.

PACS numbers: 84.60.Rb, 72.20.Pa, 84.60.Bk

## I. INTRODUCTION

Optimization of thermoelectric systems for energy conversion applications not only involves the improvement of the materials' properties to enhance the so-called figure of merit, but also a strategic reflexion on device design [1]. The segmentation of thermoelectric legs in a module is one of the strategies used to yield the best possible performance of the materials. A segmented leg is obtained by stacking different thermoelectric materials in such a way that each part of the leg is optimized for the temperature that it experiences within the structure. The basic principle of this technique lies in the temperature-dependence of the materials' properties: a given material presents interesting conversion capabilities only within a limited temperature range. So, when the figure of merit of a given material collapses at some point of the leg because of the variation of temperature along the leg, this material is replaced at this point by another one, better suited to the local temperature. The benefits on the global performance of the device is obvious when the temperature difference imposed on the TEG is important [2]. A high performance leg is composed of different segments thermally and electrically in series.

The principle of segmentation was patented in 1962 [3]. However this segmentation strategy is not always the best solution to achieve high power efficiency as it was pointed out many times and even before the publication of the patent. Thus, along the years, many criteria were selected and used to see if the global efficiency could sufficiently increase by segmentation. If some studies focused on local entropy production [4] and differential output power [5], others developed more global ap-

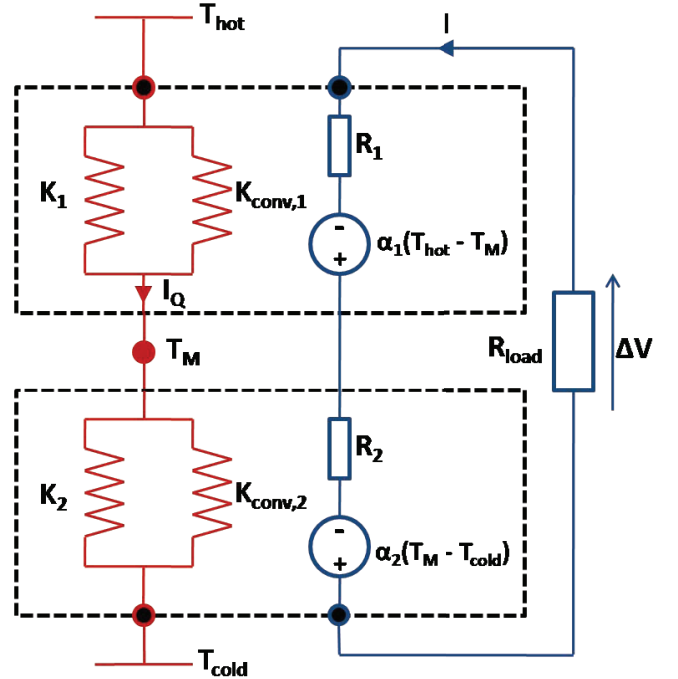


FIG. 1. Schematic representation of a segmented thermoelectric generator composed of two parts.

proaches [6, 7]. Recently Snyder and Ursell proposed the so-called compatibility approach giving a rule of thumb based on a compatibility factor associated with each material [8, 9]. The associated thermodynamic framework was further discussed in Ref. [10]. Our purpose here is to highlight the underlying physical mechanisms permitting or not compatibility between different thermoelectric materials. We focus on the simple case of a leg composed of only two thermoelectric segments. Even if the method

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is intended to be applied to materials with temperature-dependent parameters, for the sake of simplicity in this article, we develop and analyze a model with constant parameters.

Our paper is organized as follows. In Sec. II, we present our model of a two-segment thermoelectric generator; we focus especially on the equivalent series parameters and figure of merit and on their physical meaning. Then in Sec. III we compare our derivations to the so-called compatibility approach of the segmented generators, demonstrating that the latter works accurately only under restrictive conditions. In Sec. IV, we relate the system treated in this article to a device composed of two TEGs thermally and electrically in parallel: we highlight the fact that there is a surprising thermal/electrical symmetry between the two configurations. We end this paper with concluding remarks and an appendix where we show that the neglect of Joule heating and transferred power to the load in our model, is of no importance in the calculation of the junction temperature.

## II. EQUIVALENT MODEL OF TWO THERMOELECTRIC GENERATORS IN SERIES

### A. Definitions

We consider two thermoelectric generators labeled 1 and 2, electrically and thermally connected in series as depicted in Fig. 1. The electrical current through the resistive load  $R_{\text{load}}$ , is  $I$ . Each generator is characterized by an internal electrical resistance  $R_i$ , a Seebeck coefficient  $\alpha_i$ , and a thermal conductance under open-circuit condition  $K_i$  ( $i=1,2$ ). The voltages and temperature differences across each module are denoted  $\Delta V_i$  and  $\Delta T_i$ . The electrical currents and average thermal fluxes through each TEG,  $I_i$  and  $I_{Q_i}$ , are derived from the phenomenological force-flux formalism [11]:

$$\begin{pmatrix} I_i \\ I_{Q_i} \end{pmatrix} = \begin{pmatrix} R_i & \alpha_i R_i \\ \alpha_i R_i T & \alpha_i^2 R_i T + K_i \end{pmatrix} \begin{pmatrix} \Delta V_i \\ \Delta T_i \end{pmatrix} \quad (1)$$

where  $T$  is the average temperature of the whole system. The figure of merit of each TEG is  $Z_i T = \alpha_i^2 T / (R_i K_i)$ .

The key issue that we address in this paper is the determination of the temperature at the junction,  $T_m$ . This topic was hardly considered even though El-Genk and Saber noticed that the electrical current could have an impact on this temperature [2].

The mean heat flux inside a segment, i.e., in one of the TEGs, is given by:

$$I_{Q_i} = \alpha_i T I_i + K_i \Delta T_i \quad (2)$$

In Fig. 1 the heat conveyed by the electrical current is represented by the additional thermal conductances

$K_{\text{conv},1}$  and  $K_{\text{conv},2}$ . These conductances depend on electrical load through the electrical current  $I$  and may be expressed as [12]:

$$K_{\text{conv},i} = \frac{\alpha_i T I_i}{\Delta T_i} \quad (3)$$

This model is derived assuming that the heat flux is constant along a TEG and equal to its average value. This assumption amounts to neglect both the Joule heating and the electrical power produced, i.e., considering a TEG with small efficiency. Here, we further make the approximation that the mean temperature  $T$  can be considered as constant through the system as it is high compared to the temperature difference between the heat reservoirs. All these assumptions are consistent with the linear approximation used to describe the behavior of the segments.

### B. Temperature at the junction

Continuity of heat flux at the junction yields:

$$K_1(T_{\text{hot}} - T_m) + \alpha_1 T I = K_2(T_m - T_{\text{cold}}) + \alpha_2 T I \quad (4)$$

from which we derive the expression for the temperature at the junction between the two segments,  $T_m$ :

$$T_m = \frac{1}{K_1 + K_2} [(\alpha_1 - \alpha_2) T I + K_1 T_{\text{hot}} + K_2 T_{\text{cold}}] \quad (5)$$

For a more accurate description of the heat flux continuity, the reader may refer to the appendix, where we show that this simple approach gives results pretty close to those obtained without approximation.

Let us now focus on the electrical part of the generator. The voltage across the whole module is the sum of the voltages across each segment:

$$\Delta V = \alpha_1(T_{\text{hot}} - T_m) + \alpha_2(T_m - T_{\text{cold}}) - (R_1 + R_2)I \quad (6)$$

Substitution of  $T_m$  by its full expression (5) yields

$$\begin{aligned} \Delta V = & \frac{K_2 \alpha_1 + K_1 \alpha_2}{K_1 + K_2} (T_{\text{hot}} - T_{\text{cold}}) \\ & - \left[ \frac{(\alpha_1 - \alpha_2)^2 T}{K_1 + K_2} + R_1 + R_2 \right] I \end{aligned} \quad (7)$$

and we thus obtain an expression with the same form as the one expected for a Thévenin generator:

$$\Delta V = \alpha_{\text{eq}}(T_{\text{hot}} - T_{\text{cold}}) - R_{\text{eq}}I \quad (8)$$

where  $\alpha_{\text{eq}}$  is the equivalent series Seebeck coefficient and  $R_{\text{eq}}$  is the equivalent series electrical resistance. By identification we get the following explicit expressions for both equivalent quantities:

$$\alpha_{\text{eq}} = \frac{K_2\alpha_1 + K_1\alpha_2}{K_1 + K_2} \quad (9)$$

$$R_{\text{eq}} = R_1 + R_2 + R_{\text{relax}} \quad (10)$$

The appearance of a finite third term in the equation above is rather unexpected but, as we will explain below, it is a crucial term; its expression reads:

$$R_{\text{relax}} = \frac{(\alpha_1 - \alpha_2)^2 T}{K_1 + K_2} \quad (11)$$

When considering the system in the open circuit consideration we find that the equivalent thermal conductance  $K_{\text{eq}}$  for the whole system is given by

$$K_{\text{eq}} = \frac{K_2 K_1}{K_1 + K_2}, \quad (12)$$

which is a standard form for an equivalent series conductance.

### C. On the meaning of $R_{\text{relax}}$

The quantity  $R_{\text{relax}}$  is proportional to the difference between the Seebeck coefficients  $\alpha_1$  and  $\alpha_2$ , which clearly shows that in presence of materials with significantly different thermopowers, the standard form for the equivalent series resistance does not apply; further, note that  $R_{\text{relax}}$  is by no means related to an electrical contact resistance at the interface between the two segments, which we neglect in our model. Its appearance in Eq. (10) is directly related to the relaxation of the temperature at the junction  $T_m$ , which depends on the value of the electrical current  $I$ . Indeed, to ensure thermal continuity at the interface, when the convective part of the thermal current varies, the conductive part must change accordingly to account for the modification of the temperature at the junction.

Thus when for exemple  $\alpha_1 < \alpha_2$ , as the electrical current is constant along the whole system, the conductive part of the thermal flux is larger in the second segment than it is in the first one. Thus, to satisfy the condition of continuity of the thermal flux, the conductive part must be larger in the first segment than it is in the second one. This thermal balance can only be obtained by a relaxation of the temperature  $T_m$ . Since this difference between the convective thermal fluxes in each segment increases when the electrical current increases,  $T_m$  varies with the electrical current  $I$ , as displayed in Eq. (5). The

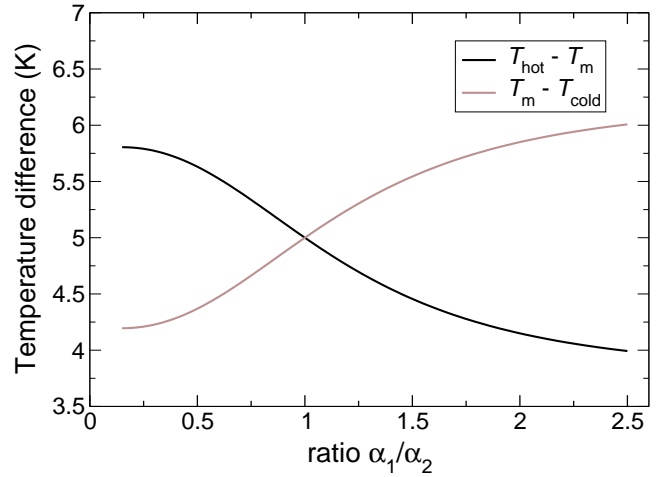


FIG. 2. Temperature difference at the edges of each segment when the global system is at maximum efficiency as a function of  $\alpha_1$  (normalized by  $\alpha_2$ ).  $TEG_1$  in full line and  $TEG_2$  in dashed line

result of such temperature relaxation at the junction always leads to increase the temperature difference at the edges of the segment exhibiting the lowest Seebeck coefficient, i.e., the one with less capability to produce power, and conversely to increase the temperature difference at the edges of the segment exhibiting the highest Seebeck coefficient: the global electromotive force developed by the whole system is thus reduced. This detrimental effect for energy conversion performances is reflected by the existence of the additional term  $R_{\text{relax}}$ .

To further discuss the consequences of the presence of  $R_{\text{relax}}$  in Eq. (10), we propose a numerical example. The parameters for  $TEG_2$  are set to the following values:  $Z_2 T = 1$ ,  $K_2 = 2.5$  mW/K,  $R_2 = 4.8$  m $\Omega$ , and  $\alpha_2 = 200$   $\mu$ V/K. These parameters are consistent with the properties at room temperature of a particular bismuth telluride compound,  $(\text{Bi}_{0.25}\text{Sb}_{0.75})_2\text{Te}_3$ , one of the most efficient thermoelectric materials [13]. For  $TEG_1$ , we make the assumption that the material used has a fixed figure of merit  $Z_1 T = 2$ , which is optimistic but remains feasible [14].  $K_1$  is also fixed, with  $K_1 = K_2$ . The thermopower  $\alpha_1$  is variable and so is  $R_1$  since it is matched to the value of  $Z_1 T$ . The reservoirs temperatures are  $T_{\text{hot}} = 305$  K and  $T_{\text{cold}} = 295$  K, and the mean temperature is  $T = 300$  K.

Figure (2) displays the dependence on  $\alpha_1$  of the temperature difference experienced by each module when the whole system works at maximum efficiency. The thermal conductances of each TEG are identical; this specification allows to obtain an equal partition of the temperature difference when there is no electrical current inside the structure. When the Seebeck coefficients are identical there is, as expected, no relaxation of  $T_m$ , but when  $\alpha_1$  differs from  $\alpha_2$ , we notice that one segment experiences a larger temperature difference. The favored side is always the one with the smaller Seebeck coefficient.

#### D. On the equivalent series figure of merit

Now that we have derived the equivalent parameters we may express the equivalent series figure of merit  $Z_{\text{eq}}$  as follows:

$$Z_{\text{eq}} = \frac{\alpha_{\text{eq}}^2}{R_{\text{eq}} K_{\text{eq}}} \quad (13)$$

which, using Eqs. (9),(10) and (12), may be rewritten as the product of two terms:

$$Z_{\text{eq}} = Y Z_{\text{series}} \quad (14)$$

with

$$Z_{\text{series}} = \frac{\left( \frac{K_2 \alpha_1 + K_1 \alpha_2}{K_1 + K_2} \right)^2}{\frac{K_1 K_2}{K_1 + K_2} (R_1 + R_2)} \quad (15)$$

and

$$Y = \frac{1}{1 + \frac{(\alpha_1 - \alpha_2)^2 T}{(R_1 + R_2)(K_1 + K_2)}} \quad (16)$$

The term  $Z_{\text{series}}$  should be seen as an *expected* term for which the equivalent series electrical resistance is given by the standard sum of  $R_1$  and  $R_2$ . The factor  $Y$ , on the contrary, is purely related to the relaxation of the temperature at the junction between the two TEGs. This factor reflects the fact that this relaxation always leads to a decrease of the performance; it is indeed smaller than 1 except for  $\alpha_1 = \alpha_2$ . It is also interesting to note that the thermal conductances and electrical resistances also appear in the expression of  $Y$  and that these quantities must be small for  $Y$  to have a significant impact on  $Z_{\text{eq}}$ .

Figure 3 obtained for the same numerical parameters as above, illustrates the fact that in order to optimize  $Z_{\text{eq}}$ , one has to make a compromise between the mere association of the segments, represented by  $Z_{\text{series}}$ , and the effect resulting from the mismatch between the Seebeck coefficients, represented by  $Y$ . The attenuation of the performances due to the thermopower mismatch calls to mind the concept of thermoelectric compatibility discussed by Snyder and Ursell [9].

To end this section on the equivalent series figure of merit, we want to stress that Bergman and Levy's theorem is satisfied:  $Z_{\text{eq}} T$ , given by Eq. (14), is always smaller than that of the segment with the highest figure of merit [15]. In the next section we compare our treatment of segmentation to that of the compatibility approach.

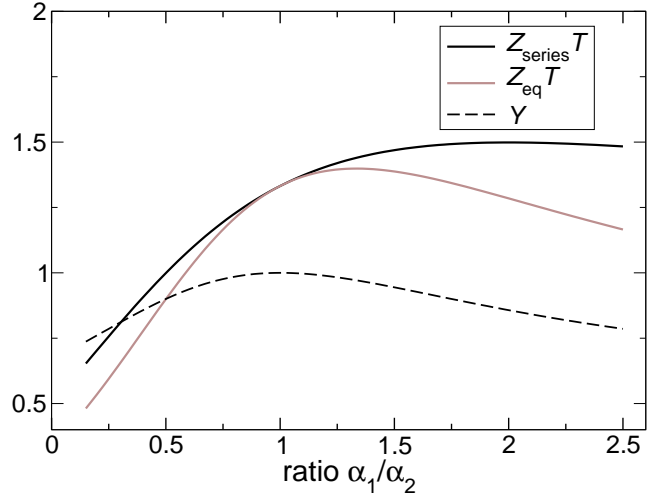


FIG. 3.  $Z_{\text{eq}} T$ ,  $Z_{\text{series}} T$  and  $Y$  plotted against the ratio  $\alpha_1/\alpha_2$ .

### III. ON THE THERMOELECTRIC COMPATIBILITY

The optimization of segmented TEGs is inseparable of the concept of thermoelectric compatibility developed by Snyder and Ursell [9]. We show in this section that our approach is, to some extent, indeed different from the compatibility approach, and we explain why we observe a discrepancy between the results given by both methods.

To evaluate the difference between the two approaches, we first remind the definitions of the physical quantities pertaining to the thermoelectric compatibility. The relative current  $u_i$  for TEG  $i$  is defined as:

$$u_i = \frac{\mathbf{J}}{\kappa_i \nabla T_i} \quad (17)$$

where  $\mathbf{J}$  is the electrical current density and  $\kappa_i$  the thermal conductivity under open-circuit condition. The macroscopic expression for the relative current is:

$$u_i = \frac{I}{K_i \Delta T_i} \quad (18)$$

The compatibility factor  $s$ , namely the optimal value for the relative current  $u$  is expressed as:

$$s_i = \frac{\sqrt{1 + Z_i T} - 1}{\alpha_i T} \quad (19)$$

Two materials are considered compatible only if their compatibility factors are close (within a factor of 2) [8]. This condition can be viewed as a necessity to have optimal values of the electrical currents in each segment, which are close enough: in this way, as the current is the same through the device, each segment works optimally at the same time [16].

Our method is based on the optimization of the equivalent series figure of merit  $Z_{\text{eq}} T$  defined in Eq. (14) and

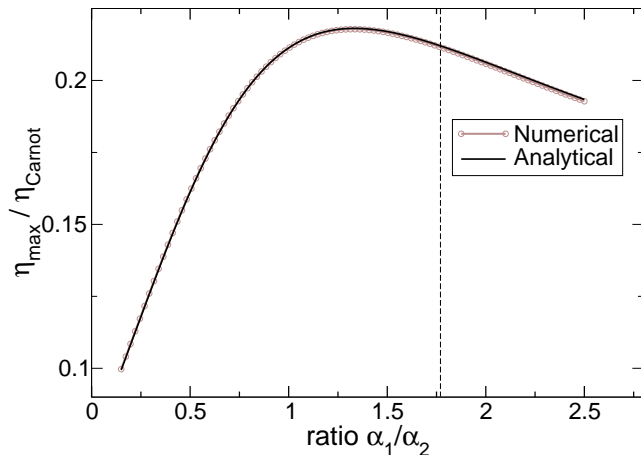


FIG. 4. Maximum efficiency (scaled the Carnot efficiency) as a function of  $\alpha_1$  evaluated both numerically and from Eq. (20).

displayed in Fig. 3 for the particular case considered in this paper. To check that  $Z_{\text{eq}}T$  is a meaningful quantity we evaluate the maximum efficiency using the traditional expression containing the figure of merit (see, e.g., Ref. [17]) with the value of  $Z_{\text{eq}}T$ :

$$\eta_{\text{max}} = \eta_{\text{Carnot}} \frac{\sqrt{1 + Z_{\text{eq}}T} - 1}{\sqrt{1 + Z_{\text{eq}}T} + \frac{T_{\text{cold}}}{T_{\text{hot}}}} \quad (20)$$

The result is displayed in Fig. (4). For comparison we also plot the maximum efficiency calculated with a numerical simulation using the complete description of the device given in Eq. (1). The two curves are very close so we may conclude that  $Z_{\text{eq}}T$  is a proper parameter to estimate the efficiency capability of the whole device.

With the case considered in this paper, the value of  $\alpha_1$  that permits satisfaction of the condition  $s_1 = s_2$ , is given by  $\alpha_1 = \alpha_2 \frac{\sqrt{1 + Z_1T} - 1}{\sqrt{1 + Z_2T} - 1} = 1.77 \alpha_2$  (vertical dotted-line in Fig. (4)) whereas with our equivalent model we find an optimal value of  $\alpha_1 = 1.34 \alpha_2$ , which, when compared to the numerical result, leads to a better optimization for the maximum efficiency.

Why the compatibility approach fails to accurately predict the optimal set of parameters in this particular case? To derive their expression of the compatibility factor  $s$ , it appears that Snyder and Ursell assumed that heat transport by conduction remains constant along the device: “*Since all segments in a thermoelectric element are electrically and thermally in series, the same current  $I$  and similar conduction heat  $A\kappa\nabla T$  flow through each segment*” [9]. This assumption is more explicitly stated in Ref. [16]. However, as soon as the figure of merit varies from one segment to the next one, the partition of heat flux between the convective and the conductive contributions changes along the device. As derived in Ref. [18],  $ZT$  may indeed be related to the ratio of these two contributions and it follows that, in order to guarantee the

satisfaction of the condition of heat continuity (though, still neglecting the produced power and the Joule effect at the interface) the conductive part given by  $K_i\Delta T_i$  is internally set to the appropriate value through the relaxation of  $T_m$ . The compatibility approach thus loses accuracy when the figures of merit of each segment are both high (i.e. greater than 1) and relatively dissimilar, which is the case of the numerical example treated in this paper. The determination of the relative current at a local scale through numerical simulations remains a powerful tool for device optimization nonetheless, as it allows to deal with generators composed of more than two segments and with materials characterized by non constant parameters [16, 19, 20].

#### IV. COMPARISON BETWEEN SERIES AND PARALLEL CONFIGURATIONS

In a recent article [21] we studied the association of two TEGs electrically and thermally connected in parallel: we demonstrated that if the Seebeck coefficients of the two segments composing the device are different, an internal electrical current may develop and yield an additional term for the equivalent parallel conductance under open circuit condition. This additional term,  $K_{\text{conv}}$ , results from the convection process, i.e. heat that is conveyed by the electrical current inside the structure. Note that in Ref. [21] we used the word *advection* but we realized since then that *convection* is better suited to characterize this heat transport process. The conductance  $K_{\text{conv}}$  reads

$$K_{\text{conv}} = \frac{(\alpha_1 - \alpha_2)^2 T}{R_1 + R_2} \quad (21)$$

At this stage, it is instructive to highlight the similar forms of Eq. (21) and Eq. (11): both expressions are proportional to the square of the difference of the Seebeck coefficients, and one may switch from one to the other only by exchanging the nature of the physical property under consideration: one only needs to replace the electrical resistance by the thermal conductance and *vice versa*. It is interesting to point out that the underlying symmetry between thermal and electrical transport in thermoelectric phenomena is reflected by the correspondence between these two equations. Indeed we notice that the electrical transport impacts the thermal transport in the parallel configuration as much as the thermal transport impacts the response of the electrical circuit in the series configuration.

We pursue the comparison between both cases: as for the series configuration, the equivalent parallel figure of merit may be expressed as the product of an *expected* term and the factor  $Y$  as defined in Section II.

$$Z_{\text{eq}}^{\parallel} T = Y \frac{(G_1 + G_2) \left( \frac{G_1 \alpha_1 + G_2 \alpha_2}{G_1 + G_2} \right)^2}{K_1 + K_2} T \quad (22)$$

which yields the following definition of the equivalent parallel thermopower and conductance:

$$\alpha_{\text{eq}}^{\parallel} = \frac{G_1 \alpha_1 + G_2 \alpha_2}{G_1 + G_2} \text{ and } G_{\text{eq}}^{\parallel} = G_1 + G_2 \quad (23)$$

where for convenience, in the parallel case, we use the electrical conductance  $G (= 1/R)$  instead of the electrical resistance.

## V. SUMMARY

In this article we have presented a simple model of a segmented thermoelectric generator composed of only two segments. We demonstrated that when the Seebeck coefficients of each segment are different, the temperature at the junction changes as the electrical current varies. This effect is embodied in an additional term for the equivalent series electrical resistance, and reflects the associated decrease of performance. Knowledge of equivalent series parameters allowed the derivation of an equivalent series figure of merit, which accurately characterizes the efficiency capability of the whole device. By comparison of our approach to the so-called compatibility approach we demonstrated that if our simple model sheds light on the mechanism of temperature relaxation at the junction between each segment, the compatibility factor fails to account for this fact. However, at the local scale, the relative current remains a suitable and powerful tool for efficiency optimization. Indeed it allows consideration for devices composed of more than two segments, made with materials characterized by temperature-dependent parameters. Finally we have highlighted the symmetry that exists between the association of TEGs in parallel and the association in series.

## ACKNOWLEDGMENTS

This work is part of the SYSPACTE projects funded by the Fonds Unifié Interministériel 7. Y. A. acknowledges financial support from the Ministère de l'Enseignement Supérieur et de la Recherche.

## Appendix A: Approximate expression against exact expression

In this article, for simplicity we used an approximate description of the TEGs, neglecting both Joule heating and power transferred to the load, in order to derive the expression of the temperature  $T_m$ . We show here that the approximations we made is justified. To do so, we compare the results obtained with Eq. (5) and from the following exact expression derived from the full condition of continuity of the heat flux at the junction:

$$T_m = \frac{K_1 T_{\text{hot}} + K_2 T_{\text{cold}} + \frac{(R_1 + R_2)}{2} I^2}{K_1 + K_2 + (\alpha_2 - \alpha_1) I} \quad (\text{A1})$$

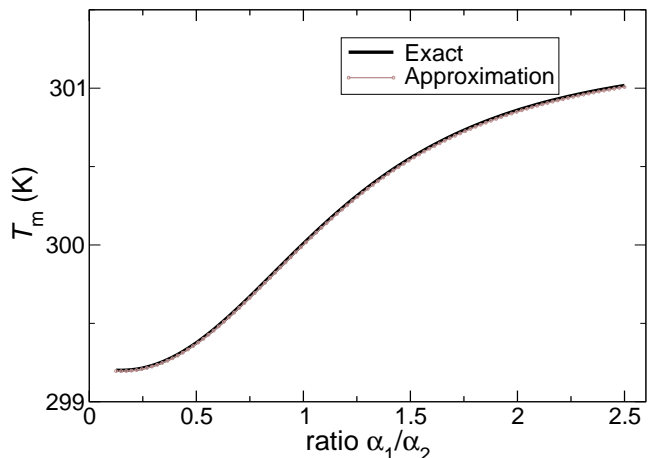


FIG. 5. Comparison of the exact and approximated values of  $T_m$  for the maximum efficiency working condition as a function of  $\alpha_1$ .

Retaining the same values of the parameters used for the numerical example treated in the main text, figure 5 displays the dependence on the thermopower  $\alpha_1$  of  $T_m$ , given by Eq. (5) and by Eq. (A1) when the whole system works at maximum efficiency. We notice that the approximation holds very well for the different values of  $\alpha_1$ . However, the exact value always is slightly larger than the approximated one: this discrepancy is due to the Joule heating, neglected in the approximation, which raises a little the internal temperature of the structure.

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